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RESEARCH AND DEVELOPMENT
OF
CACHE MARKER SYSTEM

PHASE I: INVESTIGATION AND EVALUATION

Covering the Period:

1 July 1952 - 30 November 1952

Contract No. [redacted]

50X1

12 December 1952

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TABLE OF CONTENTS

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Abstract

This report describes an investigation to determine the feasibility of a cache marker system. An experiment in magnetic coupling showed that reasonable amounts of energy could be transferred from the detection device to the transponder. The various methods that were investigated for detecting the transponder by means of this transferred energy are described. Two single-frequency systems have been developed which are capable of detecting the transponder at distances up to about 30 feet in air. Calculations indicate that large deviations from the results in air should be encountered only in sea water.

Theoretical investigation indicates that the Q of the coils of the transponder and of the detection device should be as large as possible. Litz wire offers an improvement in Q over solid wire by a factor of 2 or more. A spider-web type winding seems to offer the best coil configuration. A Q of 375 has been obtained using Litz wire in a spider-web type winding.

I. INTRODUCTION

A. Purpose

The purpose of this project has been to investigate the feasibility of developing a system to locate exactly a previously buried (or submerged) object (cache), whose approximate position is known. As outlined in the proposal, this system should consist of a transponder which is buried or submerged in the vicinity of the cache and a detection device for locating the transponder and thus the cache.

B. System Requirements.

The requirements that have been suggested which the system must satisfy are as follows:

1. The system shall include everything necessary to attain the desired result including a transponder and a means for detecting its location under specified conditions.
2. The system shall be capable of revealing the exact location of the transponder at a radius of at least 15 feet when the transponder is buried (or submerged) at a depth of 5 feet below the surface of the ground (or water). If this depth cannot be realized, then the depth shall be at least inaccessible to the conventional mine detector. This is presently estimated to be about 2 feet.
3. The system shall operate reliably in all varieties of soil and under water.
4. A single technique of universal application is desired.
5. The system shall be secure from ordinary attack and from accidental disclosure of the cache to the greatest extent practicable.

50X1

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6. The system shall be operable by non-technical personnel.

7. The transponder shall be relatively inexpensive.

8. The transponder shall be passive.

9. The transponder shall be of construction estimated to operate reliably 5 to 10 years[1] after being placed as specified in requirement 2.

10. The detection device shall be readily portable by one man and capable of operation without apprehension by a casual observer.

C. Means of Energy Transfer

The solution of this problem requires a means of transferring energy to the transponder which, in turn, transfers this energy back to the detector, thus indicating its presence. The factor considered in the process of determining the most profitable line of attack was the question of attenuation in the medium of the propagated energy.

1. Sound Waves

The absorption factor for sound in sand and soil has been reported by Nyborg et al[2] for the frequency range of 10 to 100 kc. The results show a sound level decrease of 40 db. at 35 kc. as compared to 20 db. at 10 kc. when the distance from the transmitter is doubled. This was for the case of mud and the attenuation.

[1] This condition rules out the possibility of using presently available batteries.

[2] Nyborg, W. L.; Rudnick, I.; Schilling, H. K., "Experiments on Acoustic Absorption in Sand and Soil", Journal of the Acoustical Society of America, Vol. 22, No. 4 (July 1950) pp. 422-425.

factor increased as the water content of the medium decreased. There was some hope that at very low frequencies the attenuation for sound would be greatly reduced. An acoustical driver was built to measure the attenuation at low frequencies but the delay in obtaining a pickup for measuring the sound level prevented us from carrying out this portion of the program.

2. Electrical Conduction

The current distribution in the medium determines whether electrical conduction could be used to transmit energy to the transponder. This method was not followed up because the current distribution is largely determined by the conductivity of the medium, which varies over wide limits. Time did not permit an investigation to determine whether a system could be made operable over these limits.

3. Electromagnetic Fields

The attenuation of electromagnetic waves and magnetic fields is small provided the frequency is not too large. The equation for the attenuation as a function of frequency, conductivity and dielectric constant is given in Appendix A. In addition, the dielectric constant and conductivity for various soils and water are presented. The attenuation factor is calculated for various media at a frequency of 100 kc.

Some simple calculations were made which showed that sizeable voltages could be induced into tuned circuits with coils of reasonable size and a reasonable number of turns at distances of ten feet.

These calculations are presented in Appendix B and formed the basis for the fundamental experiment.

II. BASIC EXPERIMENT IN MAGNETIC INDUCTION

Two coils were made with an average radius of 1 foot, with 100 turns of AWG #18 Formvar insulated wire in a spider-web type winding. The experimental setup is shown in Figure 1.

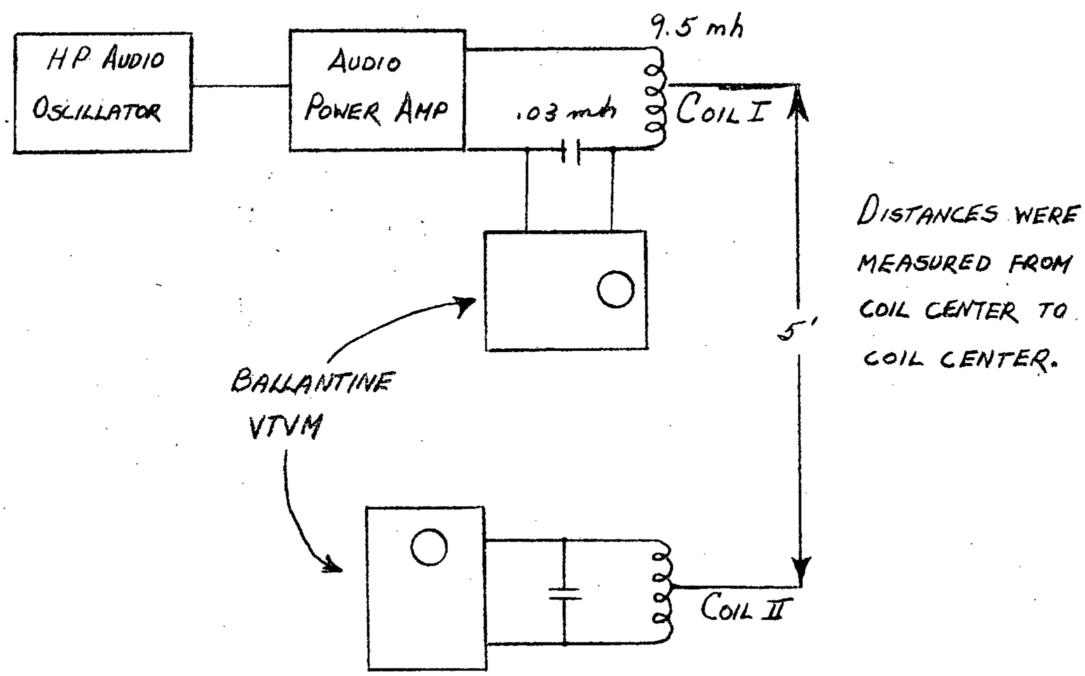

Figure 1. Diagram of Experiment

A Hewlitt Packard audio signal generator was used to drive an audio amplifier whose output was fed to a series tuned circuit adjusted for resonance. The operating frequency was about 10 kc. A Ballantine VTVM measured the voltage across the condenser. This voltage was kept at 100 V rms throughout the experiment. The voltage across Coil II was measured for various positions where the distances were similar to those specified by the requirements.

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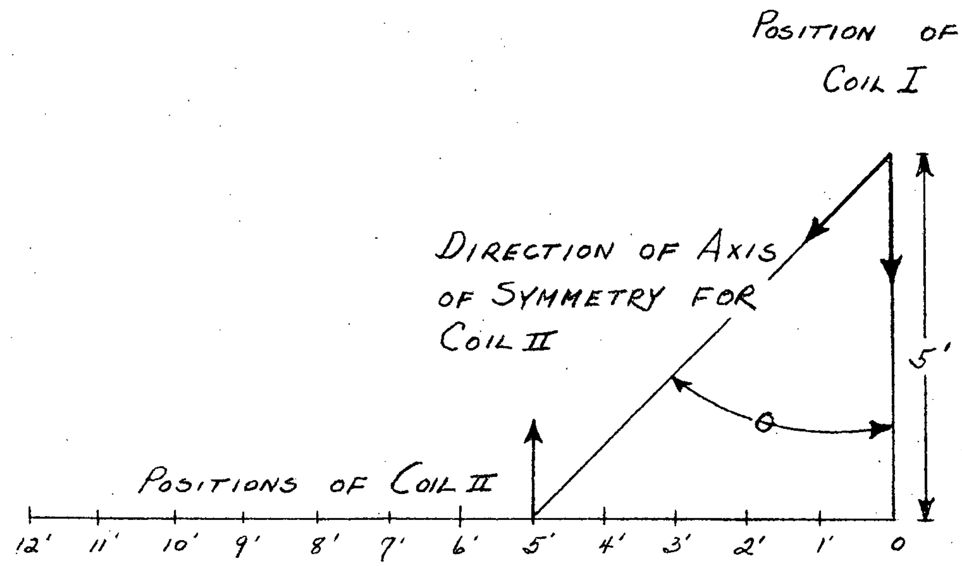

Figure 2. Geometry of Experiment

Figure 2 shows the layout of the two coils. All the dimensions refer to the centers of the coils. The axis of symmetry of Coil II was maintained as shown in Figure 2. One run was made with the axis of symmetry of Coil I maintained parallel to the axis of symmetry of Coil II. A second run was made wherein the axis of symmetry of Coil I was pointed at the center of Coil II for each measurement. These results are presented in Figure 3 where the voltages have been normalized by dividing by the voltage reading (8.2 volts rms.) obtained for Coil II in the 0 position. The abscissa for each point is the angle θ (see Figure 2) or the horizontal distance measured from 0 in terms of d which is equal to 5 feet. The theoretical curves are also presented for comparison; their derivations are given in Appendix B.

The results of this experiment demonstrated that we could profitably concentrate our efforts on trying to find a method of detecting the energy

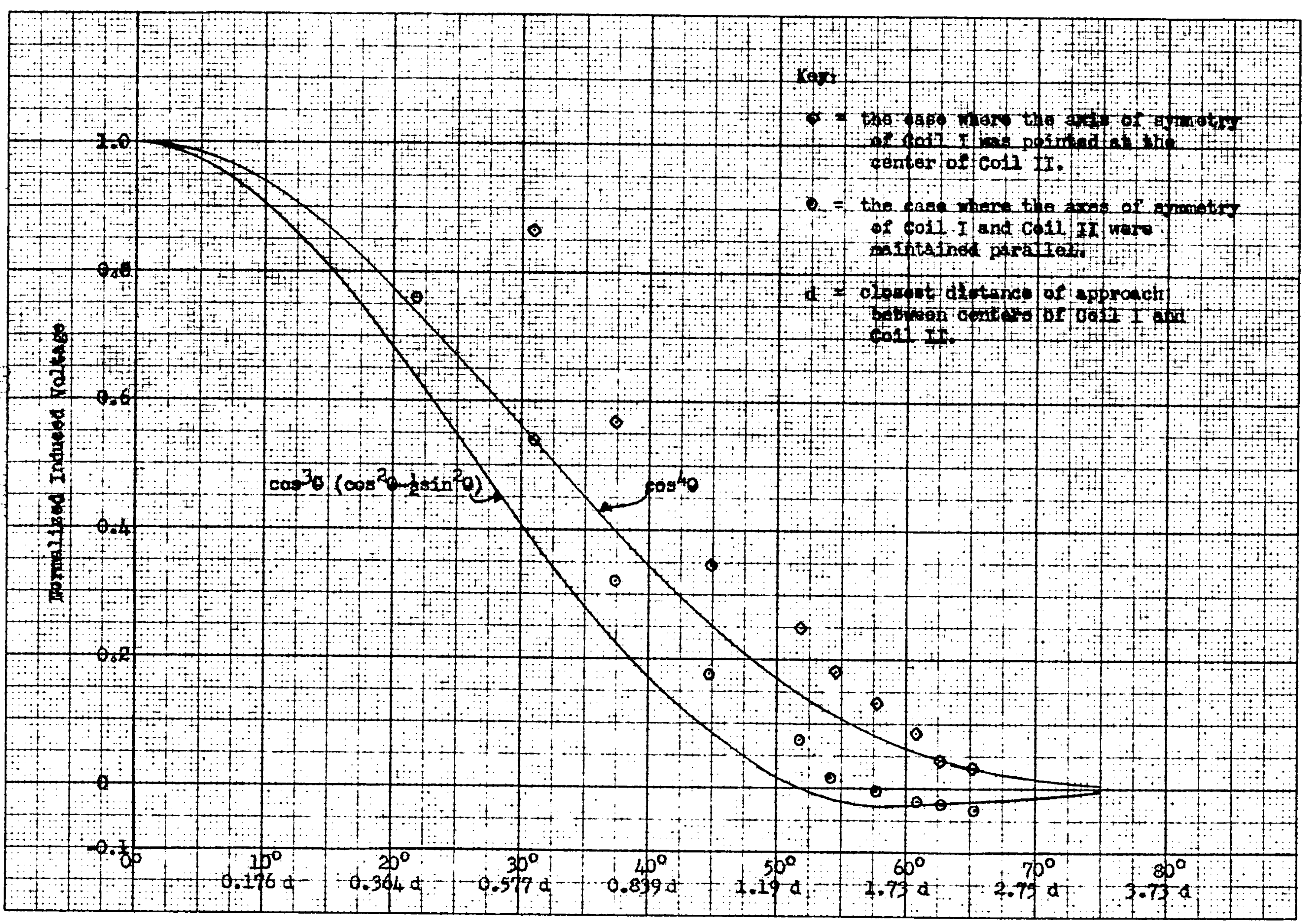

Figure 3. Horizontal Distance from Position 0

III. THE DETECTION SYSTEMS INVESTIGATED

The sections that follow describe our efforts in the development of a feasible system for detecting the transponder by means of magnetic coupling. They are given more or less in the order in which they occurred.

We first started with the idea of developing a two-frequency system. Our early thoughts were to have both frequencies present in the transmitted signal. We soon realized that this requires bandwidth, which decreases as the Q goes up. Thus, in order to have flexibility in the choice of frequency, the transponder would be required to have two separate tuned circuits in the input.

The single-frequency pulsed system was the first one-frequency system considered and the crossed coils system was the second. The balanced coil system is also included for discussion although no experimental work was performed on this system.

Coil I and Coil II refer to the coils described in the basic experiment. The coils had an inductance of 9.5 mh and a Q of approximately 100.

A. Balanced Bridge System.

This system consisted of an oscillator driving an audio amplifier which fed a bridge circuit as shown in Figure 4.

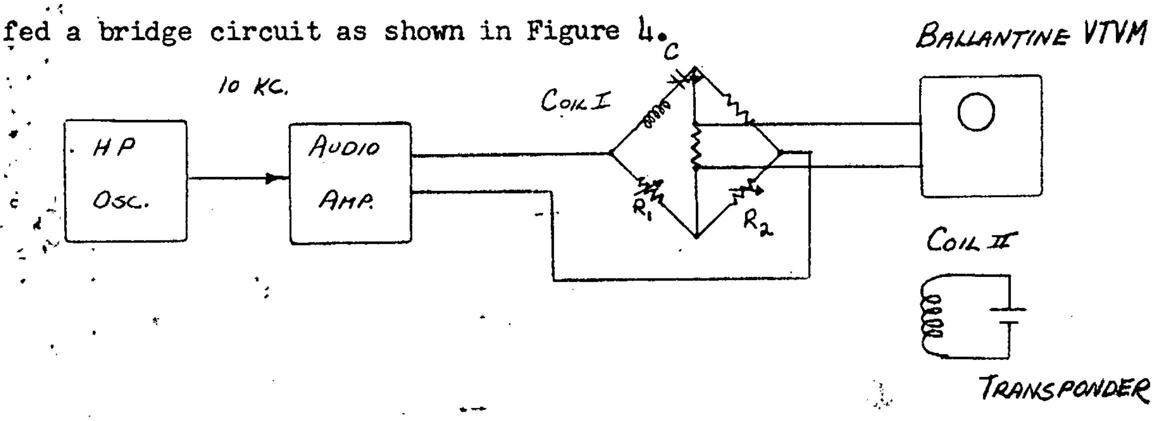

Figure 4. Diagram of Bridge Circuit

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Three legs of the bridge were resistors; the fourth leg contained Coil I with C in series tuned to resonance, the leg thus appearing as a pure resistance. The bridge balanced by adjustment of R_1 and R_2.

The object of this system was to detect the presence of the transponder by means of unbalancing the bridge circuit due to the reflected impedance in Coil I. The transponder was tuned to resonance which made the reflected impedance resistive.

One difficulty we found with this system was the inability to obtain a good null because the balance is frequency sensitive and and a null can occur for only one frequency at a time. Any distortion in the voltage applied to the bridge gives rise to a residual voltage at the null which is made up of all frequency components present in the applied voltage except for that frequency to which the bridge is tuned.

With the null obtained there was an observable change with the transponder at about 2 feet. This could have been improved by use of a tuned amplifier. However, this system is essentially a form of a mine detector and would respond to any piece of metal which would cause a resistance to be reflected in Coil I thereby unbalancing the circuit. No additional work was done on this system.

B. Colpitts Oscillator

This system consisted of a Colpitts oscillator, a signal generator and a receiver.

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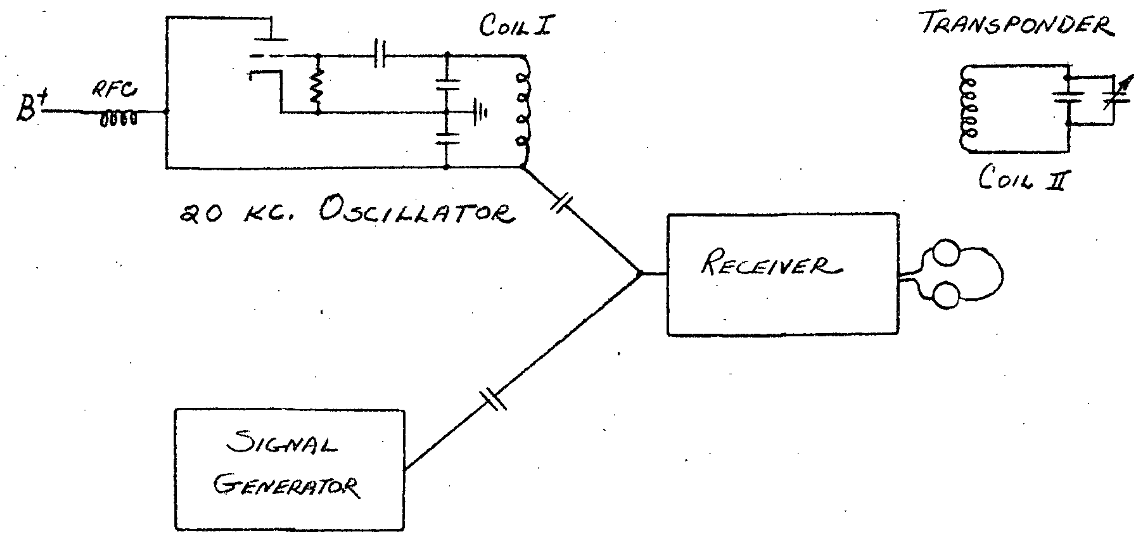

Figure 5. Diagram of Colpitts Oscillator System

The ability of this system to detect the transponder depends on the oscillator frequency change, that is the result of the reflected impedance appearing in Coil I due to the presence of the transponder. The reflected impedance is a resistance exactly at resonance. If the transponder is tuned slightly off resonance the reflected impedance is complex being partly inductive and partly capacitive, depending on which side of resonance the transponder is tuned.

This system was tried with the oscillator tuned to 20 kc. The signal generator and receiver were tuned to about 1600 kc. or the 80th harmonic of the oscillator. We could thus hear the beat between the 80th harmonic of the oscillator and the output of the signal generator. With this system the transponder could be detected up to a distance of about 4 feet by listening to the change in the frequency of the beat note heard in the receiver. It was felt that no real improvement could be made on this system and no further investigation was made.

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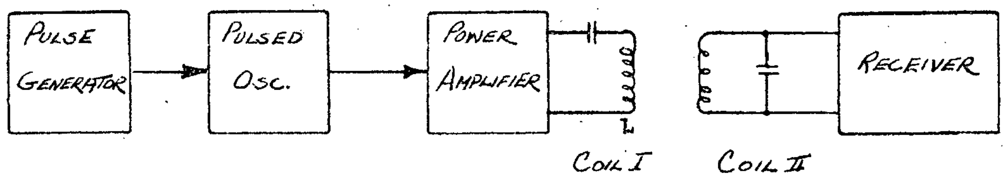
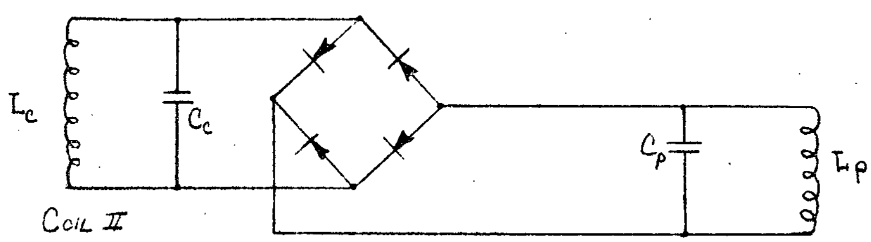
C. Two-Frequency Pulsed System

This system consisted of a pulse modulated transmitter and a receiver tuned to the pulse repetition frequency as shown below, Figure 6.



DETECTION DEVICE



TRANSPONDER

Figure 6. Diagram of Two-Frequency Pulsed System

The transponder is made up of two tuned circuits: L_cC_c, which is tuned to the frequency of the pulsed oscillator (about 40 kc.), and L_pC_p, which is tuned to the repetition rate of the pulse generator (about 5 kc.), connected together through a bridge rectifier circuit made up of 1N51 diodes.

A brief description of how, in principle, this system operates can best be told in terms of the waveforms shown below.

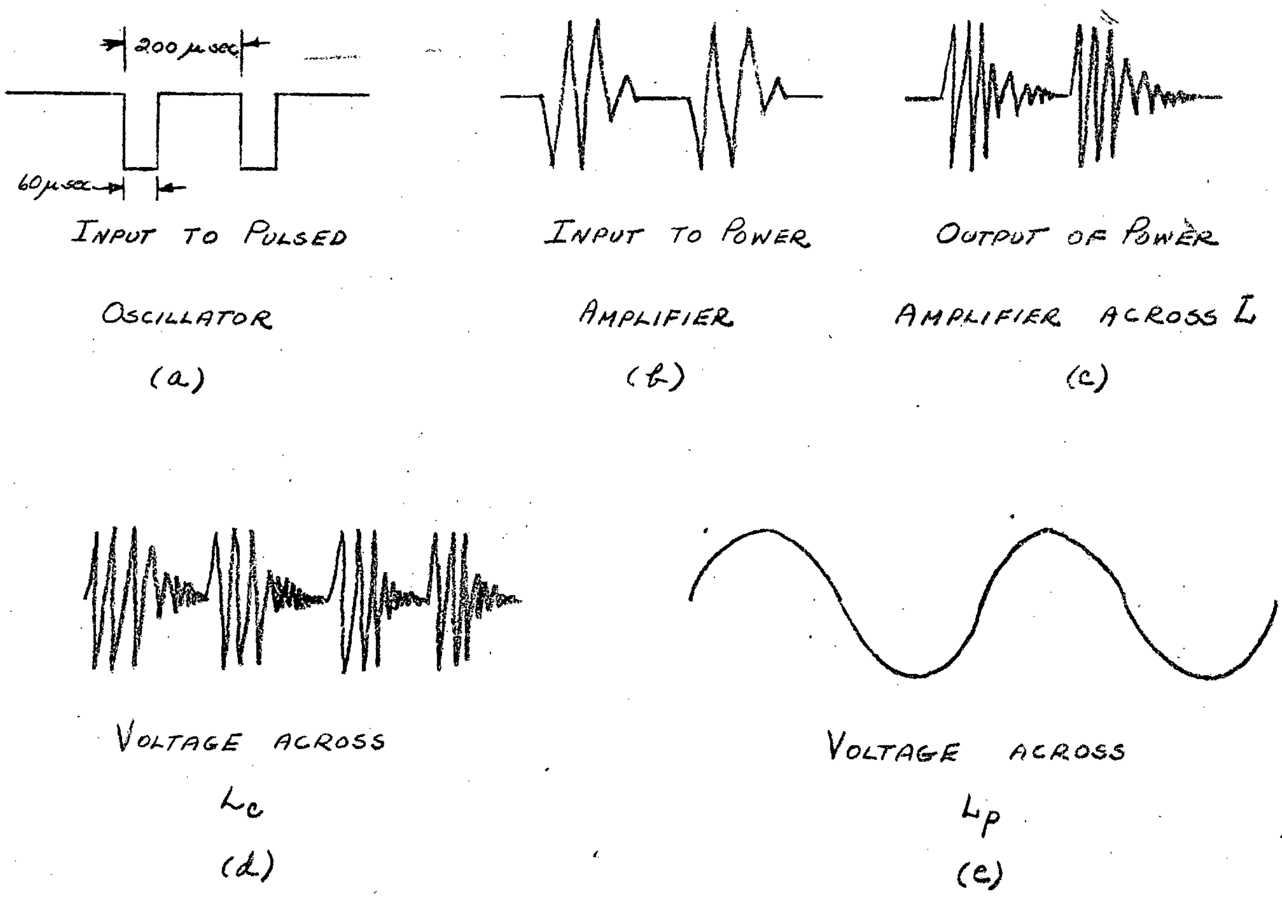


Figure 7. Waveforms for Two-Frequency Pulsed System

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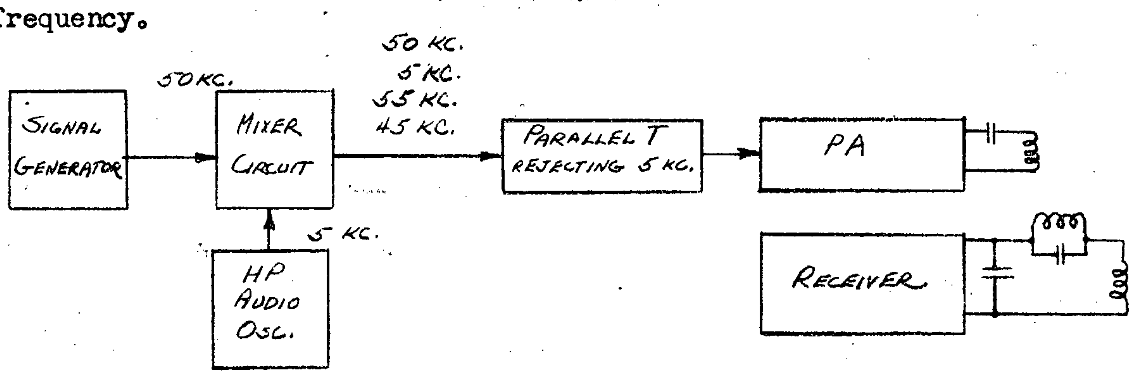
The pulsed oscillator is triggered with negative pulses from the pulse generator [Figure 7(a)] and oscillates during the duration of these pulses [Figure 7(b)]. The output of the power amplifier is shown in Figure 7(c) and this is the form of the magnetic field produced by L. This induces a voltage in the transponder L_c as shown in Figure 7(d). This signal is rectified and filtered by L_pC_p giving the waveform shown in Figure 7(e). The receiver input is tuned to the same frequency as L_pC_p and has a voltage induced in the receiver coil by the circulating current of L_pC_p.

The difficulty encountered in this system was in the coupling between transmitter and receiver coils. The pulses of 40 kc. signal in the transmitter coil shock excited the receiver coil, resulting in a 5 kc. signal without the action of the transponder.

The next step in our investigation was to devise a system similar to the two-frequency pulsed system in that both frequencies were present in transmitted signal but where shock excitation would not occur.

D. Amplitude Modulation System

This system consisted of an amplitude modulated transmitter, where the modulating frequency corresponds to the role of the pulse repetition rate in the Two-Frequency Pulsed System, and a receiver tuned to this frequency.



plitude Modulation System

The mixer circuit of the transmitter is fed with 5 and 50 kc. signals giving outputs of 5, 50, 45 and 55 kc. signals. These are applied to a parallel T RC network tuned to 5 kc. which attenuates signals of this frequency. The other signals pass through relatively unattenuated and are amplified by the power amplifier and fed to tuned circuit. It was then realized that the transponder of the previous system could not be used because of the broad tuning required to pass 45 kc. and 55 kc. This would require a Q of about 5 in order to have a 10 kc. bandwidth at 50 kc. An attempt to solve this problem resulted in the transponder shown below.

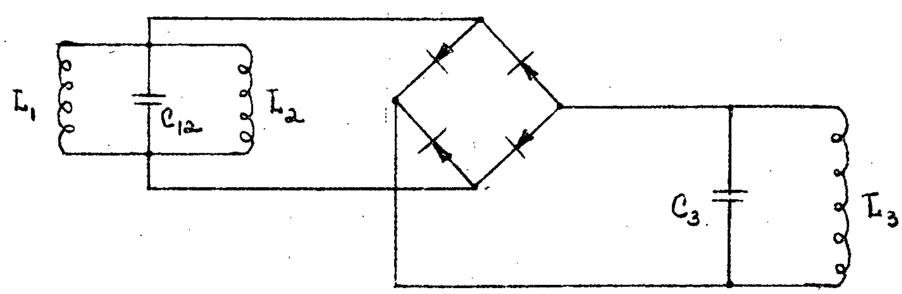


Figure 9. A Two-Frequency Transponder

The inductance L_1 C_{12} resonates at 45 kc. or 55 kc. and L_2C_{12} resonates at 50 kc. The bridge circuit serves as the non-linear element to produce a difference frequency, 5 kc, to which L_3C_3 is tuned. A theoretical analysis of the operation of this circuit was attempted which took into account the mutual inductance between L_1L_2, L_2L_3, and L_1L_3.

The analysis, although not completed because of the complexity of the problem, was not entirely devoid of useful results. It served as the motivation for asking the question of whether two-frequency systems were practicable. This is discussed in a later section.

E. Single-Frequency Pulsed System

This system consists of a pulsed transmitter and a gated receiver synchronized together by means of a gate-pulse generator. The transmitter output induces a voltage in the transponder causing current to circulate which contines after the transmitter is off. The receiver is turned on after the transmitter is off receiving the signal due to the "ringing".

The inherent difficulty with this system was the coupling between the transmitter and receiver and the consequent "ringing" of the receiver. The first step in the solution of this problem was the use of an untuned input to the receiver. Gating was attempted in the first stage of the receiver. This resulted in gating transients which could not be completely eliminated. The difficulty was solved by going through several stages of untuned amplifiers before gating. By dealing with larger signals the gate tube could be operated so that it conducted only when a signal from the transponder was present. Let us now consider the system in more detail.

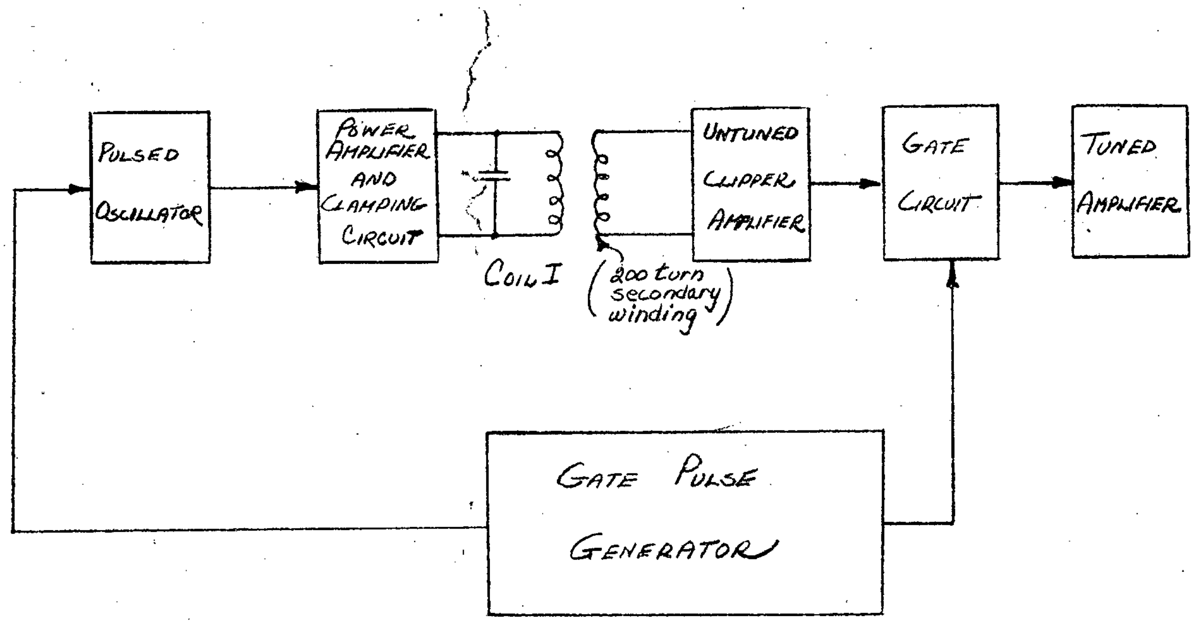


Figure 10. Single-Frequency Pulsed System

The gate-pulse generator supplies negative pulses to the pulsed oscillator and to the gate circuit. The pulses supplied to the receiver are of longer duration than those supplied to the transmitter in order to keep the rapidly decaying voltage in the transmitter circuit from entering the receiver.

The pulsed oscillator consists of a Hartley oscillator whose tank circuit is loaded down by the cathode circuit of a triode. This load is removed when the triode is cut off which allows the oscillator to operate.

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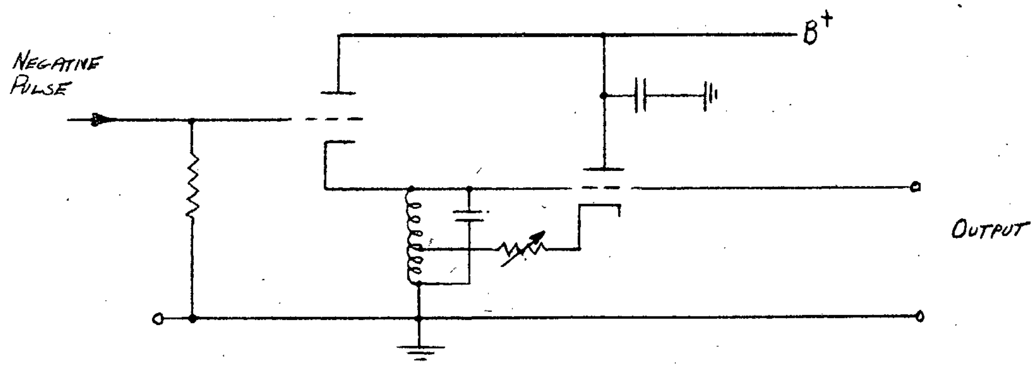

Figure 11. Pulsed Oscillator

The output of the oscillator feeds the power amplifier clamping circuit which consists of a cathode follower feeding the tuned output circuit. The cathode is connected to a tap on the inductance which

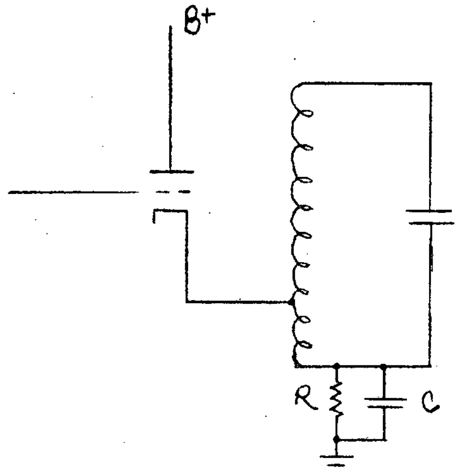

Figure 12. Power Amplifier Clamping Circuit.

is the output circuit of the transmitter. The position of the tap can be chosen to give any impedance load up to the maximum value of the tank

50X1

circuit. The tap is chosen to give an impedance which matches the output of the cathode follower. The cathode follower also acts as a clamping circuit in that it behaves as a low impedance across the tank circuit when the oscillator stops and damps out the ringing in a few cycles.

The untuned clipper amplifier consists of two stages of clipping and amplification. (See Figure 14). The clipper circuits are biased diodes which limit the peak-to-peak amplitude to a value determined by the bias voltages. This amplitude is such that it limits the signal directly from the transmitter allowing the "ringing" signal to be amplified to a level where gating can be accomplished without the transients which result from the plate current being turned on and off. This gating operation is readily described in terms of the following diagram.

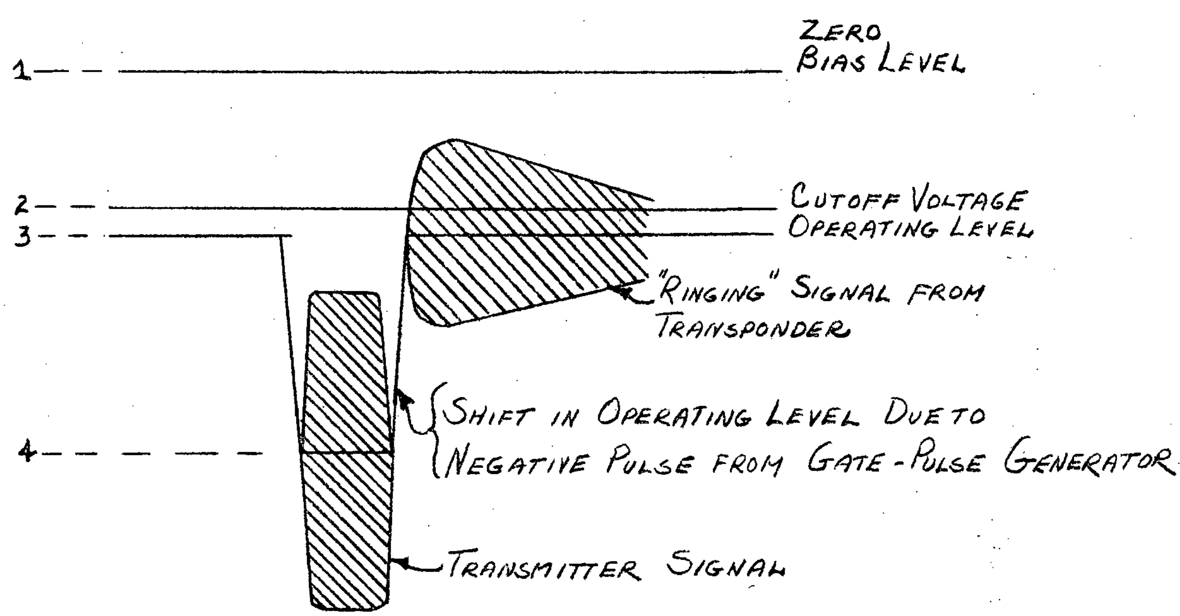

Figure 13. Operation of Gate Circuit

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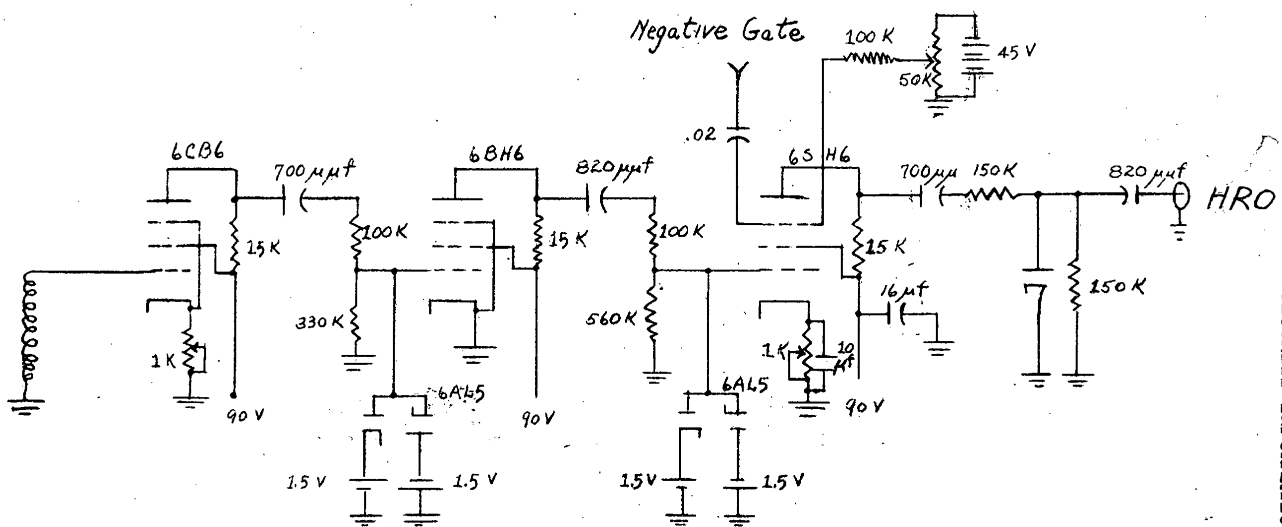

Figure 14. Clipper Amplifier and Gate Circuit

Line 1 is the zero level of the control grid. Line 2 is the cutoff level for the control grid. The control grid is operated just below this, i.e., at Line 3, except when the transmitter is on, whereupon the bias level is lowered to Line 4 by a negative pulse on the third grid of the gate tube. Thus plate current flows only when the "ringing" signal is present.

The output of the gating circuit is fed to a tuned amplifier. For this purpose we have used an HRO receiver, using the "s" meter as an indicator.

Using the circuit shown in Figure 14 the transponder could be detected at a maximum distance of 11 feet. Further work is required to improve the gating circuit and to reduce the noise.

F. The Crossed Coils System

The crossed coils system consists of a CW transmitter, a receiver and tuned coils for the transmitter output and the receiver input. The transmitter and receiver coils are oriented so that there is minimum coupling between the two coils. The transmitter field induces a circulating current in the transponder which produces a field which induces a voltage in the receiver coil. This voltage is amplified sufficiently to be detectable. In our experiments we have used the Tektronix "scope" of an HRO receiver as an indicator.

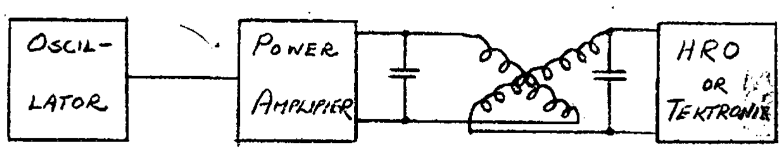

Figure 15. Crossed Coils System

The same transmitter was used for this system that was used in the single-frequency pulsed system. In order to get CW operation a constant, negative voltage was applied to the grid of the triode controlling the Hartley oscillator.

The transmitter and receiver coils were wound on forms cut out of masonite. A spider-web type winding was used. The dimensions of the transmitter coil are 100 turns of #18 A.W.G. with an inside diameter of 24 inches and an outside diameter of 30 inches. The receiver coil which fitted inside the transmitter coil contained 150 turns of #24 A.W.G. with an inside diameter of 11 inches and an outside diameter of 15 inches. The inside and outside diameters given are for the coil windings. The receiver coil was supported inside the transmitter coil in a manner allowing rotation of the receiver coil with respect to the transmitter.

The method of testing this system was as follows. The transmitter and receiver coil were adjusted for minimum voltage across the receiver coil with the transmitter on. The Tektronix "scope" was used as an indicator. A null of about 20 millivolts peak-to-peak was obtainable. The transponder used was similar to the coils used in the first experiment on magnetic induction. It was equipped with variable as well as fixed capacity making it possible to tune the transponder through the frequency of the transmitter. The effect of this operation was observed on the "scope" as an increase in voltage across the receiver coil. Using this method the transponder was still detectable out to a distance of 30 feet. This same experiment was performed through the brick wall of the building and this had no effect on the detection of the transponder.

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In order to reduce the null, electrostatic shielding of the transmitter and receiver coil was tried. The results are tentative because of the crudeness of the experiment but coil shielding does not give a better null; it does reduce the effect of hand capacity. We plan to try and reduce the null electrically by balancing out the residual voltage of the null with a voltage of equal magnitude but opposite in phase.

G. Balanced Coil System

This system is in principle similar to the crossed coils system in that a CW system is used. It differs in the way the transmitter signal is kept out of the receiver, as shown in Figure 16.

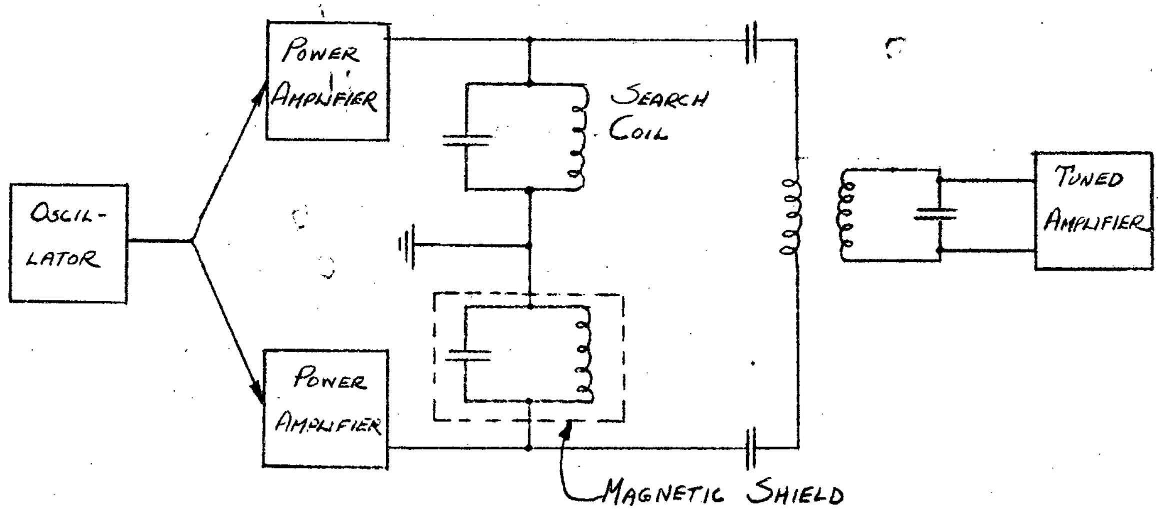

Figure 16. Balanced Coil System

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The transmitter consists of an oscillator feeding two power amplifiers working into tuned circuit loads. The tuned circuits are connected so that they are 180° out of phase and result in zero voltage input to the receiver if the amplitudes are exactly the same. The search coil produces an external field whereas the other coil is magnetically shielded, thus eliminating its external field. The circulating current of the transponder induced by the magnetic field of the search coil produces a magnetic field which induces a voltage into the search coil but none in the other coil because of the shielding. This voltage produced by the presence of the transponder appears in the input of the receiver, is amplified by a tuned amplifier and fed to an indicator.

This system has not reached the experimental stage because of lack of time; we recommend that it be considered in Phase II.

IV. CONSIDERATION OF TWO-FREQUENCY TRANSPONDERS

The reason for wanting to develop a two-frequency transponder is the added security obtained from requiring the knowledge of two frequencies to locate the transponder. It is assumed here that the enemy is completely familiar with the system and his only obstacle is the knowledge of what frequency or frequencies are used with what area and the location of the area. It is assumed the enemy does not have any restriction on the size or amount of equipment he can use. Therefore, a two-frequency transponder must not be detectable by a one-frequency detection system if it is to be considered satisfactory.

All of the transponders that we have considered contained tuned circuits which were not shielded magnetically. We cannot conceive of a transponder that works on the principle of magnetic induction which is frequency selective and does not contain unshielded tuned coils.

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The question of whether a two-frequency transponder can be detected by a one-frequency detection system is then a matter of whether a one-frequency detection system can find a tuned circuit.

We know we can find a tuned circuit of high Q. It is also possible, in principle at least, to find a tuned coil of any Q by using sufficient power in the transmitter to give a detectable amount of signal back to the receiver. The single-frequency pulsed system is an example of a system where the signal from the transponder increases with transmitter power.

We can therefore conclude that any two-frequency transponder containing unshielded tuned circuits is vulnerable to a one-frequency system attack.

V. COIL DESIGN

The coils designed for the transmitter and receiver must cover the frequency range from 50 to 150 kc. The transponder must cover the same frequency range but will be made in assorted sizes from 9 to 18 inches in diameter, the larger sizes being used at the lower frequencies.

The transmitter coil must be designed to produce the largest induced voltage in the transponder. For a given transponder and frequency this means producing the largest magnetic field possible. The magnetic field is proportional to

$$iAn \qquad 3$$

where i is the current, A is the area of the coil and n is the number of turns. From an operational point of view the area is determined by size limitations. The current i is determined by the amount of power P which is dissipated in the coil and the a.c. resistance of the coil R_{ac}. Writing $i = (\frac{P}{R})^{\frac{1}{2}}$ and dropping A since it is predetermined, the magnetic field is proportional to

$$(\frac{P}{R})^{\frac{1}{2}}n.$$

50X1

If we use the approximation that the inductance L is proportional to n^2a where a is the radius of the coil, and dropping the a for the reason above,

$$L \propto n^2$$

or the magnetic field in proportional to

$$(P)^{\frac{1}{2}} \left(\frac{L}{R}\right)^{\frac{1}{2}} \propto P^{\frac{1}{2}} Q^{\frac{1}{2}}$$

which tells us that the Q should be as large as possible.

The receiver coil must be designed so that for a given field produced by the transponder it develops the largest voltage. The voltage across the receiver coil is proportional to the number of turns n, A the area of the coil, the Q of the coil, and the frequency used. Dropping those quantities which we cannot vary, the voltage across the coil is proportional to

$$nQ.$$

The transponder coil must be designed so that for a given magnetic field from the transmitter coil, the transponder will produce the largest possible field. The magnetic field produced by a coil is proportional to

$$P^{\frac{1}{2}} Q^{\frac{1}{2}}.$$

The power, P, can be written as i^2R_{ac} or $\frac{e_i^{\,2}}{R_{ac}}$ where e_i is the induced voltage. The induced voltage is proportional to n, A, and the frequency of operation. Dropping the quantities which are determined by operational considerations,

$$P \propto \frac{n^2}{R} \propto Q \quad \text{and}$$

$$P^{\frac{1}{2}} Q^{\frac{1}{2}} \propto Q.$$

50X1

This means that for a coil whose area and operating frequency are determined, the transponder with the highest Q will produce the largest signal in the receiver for a given amount of power to the transmitter.

The problem of coil design reduces to the design of high Q coils. A preliminary investigation of this problem has indicated that a large reduction in the a.c. resistance can be expected by using Litz wire.[4] The question of the kind of winding to use is still undecided. It is stated in Henney's Radio Engineering Handbook (3rd Edition) p. 87 that honeycomb and bank wound coils are superior at frequencies below 300 kc. Our experience has been that a spider-web type winding has given us the highest Q.

Several coils were wound on a form 12 inches in diameter, 200 turns, about 1 inch wide, and with a pitch of about four inches. A honeycomb type of winding was used. The results are given in the table below.

AWG Number	L	Distributed Capacity	Frequency	Q	R_{ac}	R_{ac} R_{dc}
#18	23mh	93mmf	66.6kc	63.5	151.5	47.3
#24	25.8mh	148mmf	65kc	37	285	16.4
#30	33.8mh	232mmf	56.8kc	46.7	266	4.16
10/41	21.4mh	118mmf	60kc	33	245	3.5
52/38	21.6mh	119.5mmf	54.8kc	69	107.8	12.7

4 Butterworth, S.; "Effective Resistance of Inductance Coils at Radio Frequency, Part IV", Experimental Wireless and the Wireless Engineer, (Aug. 1926) p. 487.

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The first three coils were wound with solid wire and we note that #30 wire is better than #24 but not as good as #18. The other two coils were wound with Litz wire. The strands of this Litz wire are not braided but merely paralleled together; this kind is inferior to the type made by braiding or weaving the strands together.[5] Some improvement was made with the last coil but not a significant amount.

The same wire (52/38) was used to wind a spider-web type winding which had an inside diameter of 8.5 inches and outside diameter of 15 inches with 75 turns. This produced a coil with 2.25 mh, a distributed capacity too small to be determined accurately and a Q of 375. This seems to indicate a spider-web type winding is the most efficient form. We are now in the process of making more forms of the kind just described which will be wound with different types of wire to determine whether the high Q is the result of Litz wire or the coil geometry.

IV. CONCLUSIONS AND RECOMMENDATIONS

As a result of our theoretical and experimental investigations we can conclude that a single-frequency cache marker system utilizing magnetic coupling between the detection device and the transponder is feasible. We have experimentally developed two systems which are capable of detecting the presence of a tuned circuit (transponder) at distances up to about 30 feet.

[5] Circular 74, "Radio Instruments and Measurements", National Bureau of Standards.

These measurements have been made primarily in air although a few tests have indicated that the building wall of brick and cinder block has no noticeable effect. Field tests have not yet been made. However, theoretical calculations show that the attenuation of magnetic fields encountered in most soils can be neglected for the frequency range of 50 to 150 kc. In the case of sea water the attenuation is large in that the fields drop off to approximately 1/4 the value in magnitude after 3/4 of a meter.

The development of a single-frequency detection system which is power sensitive indicates that any two-frequency transponder using unshielded tuned circuits is vulnerable to detection by a single-frequency search system. Indeed, since the enemy has no restriction on the size and power of his equipment he can find a two-frequency transponder as easily as a single-frequency transponder, if not more easily because of the two tuned circuits.

A preliminary investigation of the problem of coil design has been made showing that the Q should be maximized for the transmitter, receiver, and transponder coil. At the frequency range of 50 to 150 kc. Litz wire offers an improvement of 2 or more in Q over solid wire. The best coil configuration appears to be a spider-web type winding but, because of lack of time and procurement difficulties, our investigations have not been sufficiently thorough in this matter to be certain.

It is recommended that the two single-frequency systems: the pulsed system, and the crossed coils system, be carried on to the engineering prototype stage in Phase II. In addition, the balanced coil system, which we have not had time to consider in this five month period, should be investigated.

VII. BIBLIOGRAPHY

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APPENDIX A

The Attenuation of Electromagnetic Waves Upon Penetration into the Earth

The attenuation of the electromagnetic wave upon entering the earth is given (in Terman's Radio Engineers' Handbook, First Edition, McGraw-Hill Book Company, New York (1943) p. 698) in terms of

$$\frac{\text{Current density at depth d}}{\text{Current density at surface}} = \epsilon^{-pd}$$

where

$$p = \left[\frac{XB}{2}\left(\sqrt{1 + \frac{(\sigma \times 10^{9})^{2}}{B^{2}}} - 1\right)\right]^{\frac{1}{2}}$$

d = depth (cm.)

X = $0.008\,\pi^{2} f_{mc}$

B = $0.556 \times 10^{-6} k\, f_{mc}$

k = dielectric constant of earth

f_{mc} = frequency, mc

σ = earth conductivity, emu

Type of Terrain	Dielectric Constant	Conductivity (emu)
Fresh water	80	1×10^{-14}
Sea water	81	4.64×10^{-11}
Sandy, dry, flat: typical of coastal country	10	2×10^{-14}
Soil (limits) -	20 to 5	3×10^{-13} to 10^{-14}

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For $f_{mc} = 0.1 \qquad X = 8 \times 10^{-4}\,\pi^2 = 7.89 \times 10^{-3}$

$B = 5.56 \times 10^{-8}\,k$

For sea water $k = 81 \qquad \sigma = 4.64 \times 10^{-11}$. Calculating p we get 1.35×10^{-2} and $\frac{1}{p} = 74$ cm. This is the depth the fields will penetrate before they drop off to $1/\epsilon$.

For fresh water $k = 80 \qquad \sigma = 10^{-14}$

$p = 2.55 \times 10^{-4} \quad \frac{1}{p} = 3.92 \times 10^{3}$ cm or 39.2 meters.

For soil $k = 20 \quad \sigma = 10^{-13}$

$p = 6.28 \times 10^{-4} \quad \frac{1}{p} = 1.59 \times 10^{3}$ cm or 15.9 meters.

We find that only in the case of sea water should we expect a large departure from the results of our experiments of magnetic coupling in air.

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APPENDIX B

The Magnetic Field and Induced Voltage for Planar Coils

We wish to calculate the voltage that is induced in a coil due to the circulating current in another coil. This is accomplished by determining the time rate of change of the magnetic flux passing through one coil due to the other coil. We assume the planes of the coils are parallel and the axes of symmetry collinear.

The magnetic field produced by a loop of wire at point p is given to a first approximation by[1]

$$\vec{H} = 2\frac{i\vec{A}}{R^3} + 3\frac{iA\sin\theta}{R^4}\vec{j}\times\vec{R}$$

where

A = Area of the loop (cm^2)

R = distance from center of loop to point p (cm)

θ = angle between Z axis and R

i = current in loop of wire (abamperes)

H = magnetic field strength (gauss)

$\vec{j}$ = unit vector in direction of Y axis

1 See for example, Page, Leigh, and Adams, Norman I., Jr., "Principles of Electricity", D. Van Nostrand Co., New York (1931) pp. 250 ff.

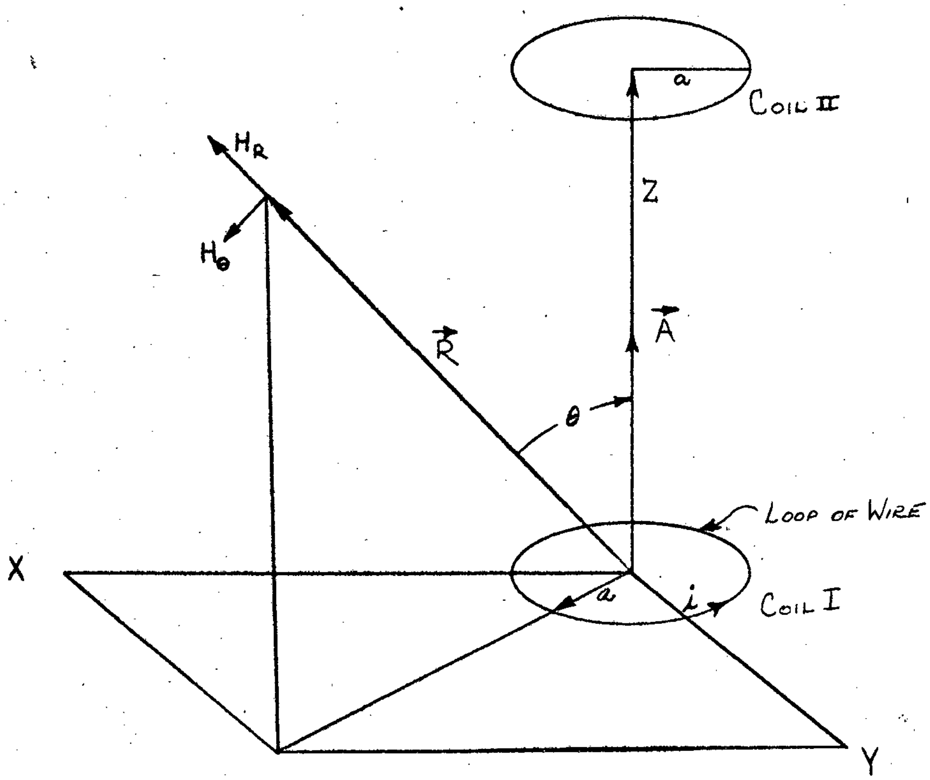

Figure 1

Taking components along $\vec{R}$ and at right angles thereto in the direction of increasing θ

$$H_R = \frac{2iA}{R^3} \cos \theta$$

$$H_\theta = \frac{iA}{R^3} \sin \theta.$$

The magnetic field in the Z direction is

$$H_Z = \frac{2iA}{R^3}.$$

Writing A as πa^2 and i as $i_o \sin \omega t$ where i_o is in practical units

$$H_Z = \frac{2\pi a^2 i_o \sin \omega t}{10 R^3}$$

for one turn and N times as great for N turns.

The induced voltage in Coil II is given by

$$e_i = \frac{-N d\phi}{dt} 10^{-8} \qquad \text{in volts,}$$

where N equals the number of turns in Coil II.

$$\phi = H \pi a^2 = \frac{2(\pi a^2)^2 N i_o \sin \omega t}{10 R^3}$$

and

$$\frac{d\phi}{dt} = \frac{2(\pi a^2)^2 N i_o \; \omega \cos \omega t}{10 R^3},$$

where N is number of turns in Coil I.

Then

$$e_i = \frac{-2(\pi a^2)^2 N^2 i_o \; \omega \cos \omega t}{10 R^3} 10^{-8}.$$

Both coils are identical. To get some idea of the order of magnitude of the induced voltage, consider the following dimensions:

$a = 25$ cm $\qquad R = 10' = 300$ cm

$N = 100 \qquad \omega = 2\pi 10^4 \quad i_o = 1$ amp.

For these values we obtain

$$e_i = .18 \cos \omega t \text{ volts.}$$

It was this calculation which suggested the basic experiment.

Now let us calculate the voltages induced for the configuration described in the basic experiment. Consider first the case where the coils are kept parallel to each other.

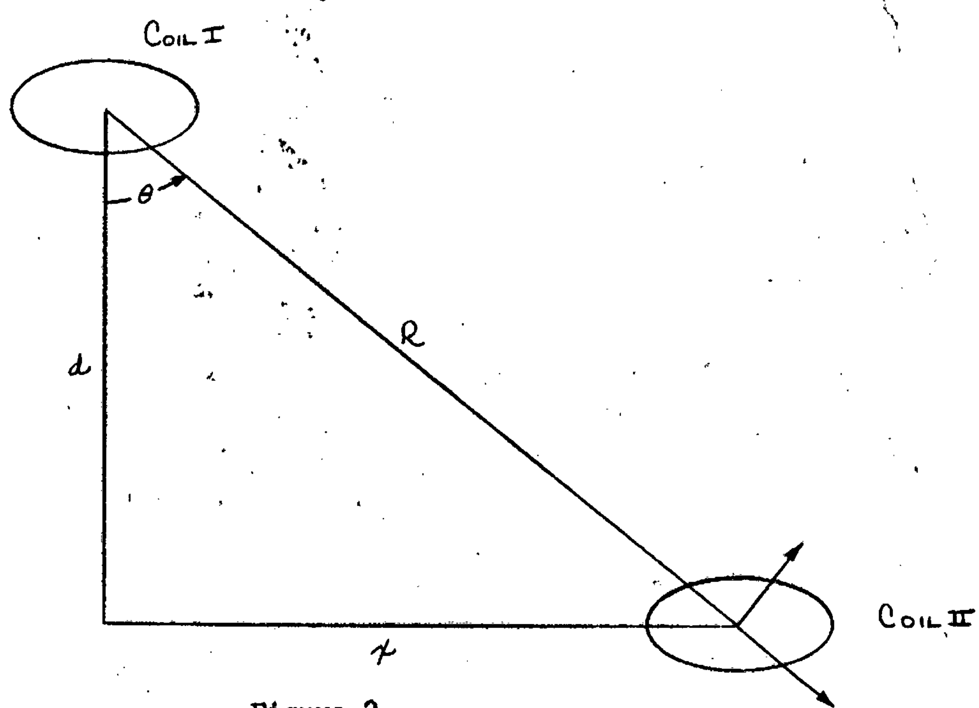

Figure 2

The voltage induced in Coil II is proportional to the normal component of the magnetic flux passing Coil II. Let us call the normal component of the magnetic field at Coil II $H_n(r,\theta)$. This can be written as

$$H_n(R,\theta) = H_R \cos\theta - H_\theta \sin\theta$$

$$= \frac{2iA}{R^3}\cos^2\theta - \frac{iA}{R^3}\sin^2\theta$$

$$= \frac{2iA}{R^3}\left(\cos^2\theta - \tfrac{1}{2}\sin^2\theta\right).$$

The induced voltage when $R = d$ and $\theta = 0$ is proportional to

$$H_n\,(R = d,\ \theta = 0) = \frac{2iA}{d^3}.$$

Then the ratio of the induced voltages when Coil II is at (R,θ) to when it is at $(d,0)$ is

$$\frac{H_n\ (R,\theta)}{H_n\ (R=d,\ \theta=0)} = \frac{\frac{2iA}{R^3}\ (\cos^2\theta - \frac{1}{2}\sin^2\theta)}{\frac{2iA}{d^3}}$$

$$= \left(\frac{d}{R}\right)^3 (\cos^2\theta - \tfrac{1}{2}\sin^2\theta)$$

or

$$= \cos^3\theta\ (\cos^2\theta - \tfrac{1}{2}\sin^2\theta)$$

since $\frac{d}{R} = \cos\theta$.

Thus

$$\frac{e_i(R,\theta)}{e_i(d,0)} = \cos^3\theta\ (\cos^2\theta - \tfrac{1}{2}\sin^2\theta).$$

Examination of this equation shows that the voltage ratio depends only on θ. Knowing $e_i(d,0)$, e_i for all values of R, θ can then be determined.

Now consider the case where the axis of symmetry of Coil I is always pointed in the direction of Coil II.

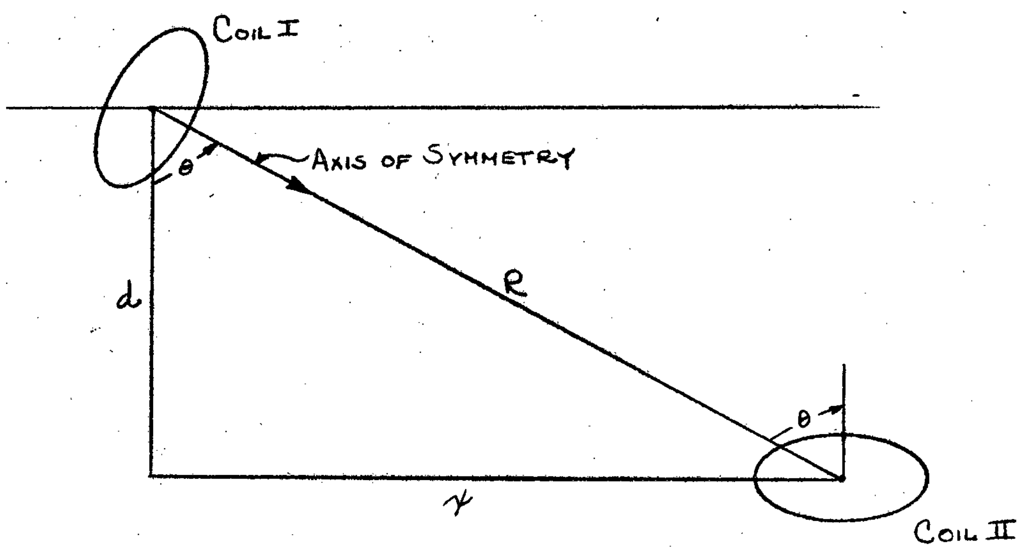

Figure 3

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In this case at Coil II there is only the magnetic field component

$$\frac{2iA}{R^3}$$

in the direction of R and the normal component is

$$\frac{2iA}{R^3} \cos \theta.$$

The magnetic field at (d,0) is still

$$\frac{2iA}{d^3}$$

and for this case

$$\frac{e_i\ (R,\theta)}{e_i\ (d,0)} = \cos^4\theta.$$